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Nonlinear Acoustics Research

Final Report under Grant N00014-89-J-1109
and Contract N00014-84-K-0574

1 August 1984 - 31 December 1995

David T. Blackstock

Prepared for: Office of Naval Research
ONR 331 • 800 North Quincy Street • Arlington, VA 22217-5660

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13. ABSTRACT (Maximum 200 words)
Research on nonlinear acoustics was carried out during the period 1 August 1984–31 December 1995. Most of the work was done as master's and doctoral research projects in one of the following general areas: nonlinear ocean acoustics; propagation; reflection, refraction, interaction, and scattering; medical ultrasonics; and miscellaneous. The research led to five master's degrees and five doctorates (including one in progress at the end of the grant) among seven students. Other participants were a postdoctoral fellow, four visiting faculty members from other universities, and a visitor from a Canadian naval laboratory. Among public disclosures of the research were 17 journal articles (of which two are not yet published), 10 papers in conference proceedings, 6 book chapters, 39 papers presented orally at national and international meetings, 9 theses and dissertations, and 18 technical reports.

14. SUBJECT TERMS
nonlinear acoustics, self-refraction, periodic medium, lithotripsy, propagation, reflection, medical ultrasound, refraction, piston radiation, scattering, diffraction, cavitation, relaxing fluid, waveguide, focusing

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1. INTRODUCTION

This is the final report under Grant N00014-89-J-1109, October 1988–December 1995. However, the report also covers all work done under the predecessor instrument, Contract N00014-84-K-0574, August 1984–December 1988. The total period of the report is thus 1 August 1984 to 31 December 1995. Some of the work under Contract N00014-84-K-0574 grew out of, or was an extension of, projects from two previous ONR contracts, N00014-75-C-0867 (April 1975–August 1984) and N00014-82-K-0805 (September 1982–November 1984). Ties to the latter two contracts are noted.

The research reported here was primarily in nonlinear acoustics. The broad purpose was to investigate the behavior of high-intensity sound waves, especially to study phenomena that have no counterpart in small-signal acoustics. In a number of cases, however, research on a topic in high-intensity sound began with, or was even dominated by, small-signal aspects of the problem.

The report is a summary. For more details, see publications or dissertations/theses cited herein or listed in the Chronological Bibliography. The following annual reports give a chronological description of the research:

- Contract N00014-84-K-0574
    1. 1st Annual Report, Period 1, August 1984–31 October 1985 (85-8)*
    2. 2nd Annual Report, 1 November 1985–31 October 1986 (86-6)
    3. 3rd Annual Report, 1 November 1986–30 September 1987 (87-4)
    4. 4th Annual Report, 1 October 1987–30 September 1988 (88-5)
- Grant N00014-89-J-1109
    1. 1st Annual Report, 1 October 1988–30 September 1989 (89-6)
    2. 2nd Annual Report, 1 October 1989–30 September 1990 (90-4)
    3. 3rd Annual Report, 1 October 1990–30 September 1991 (91-5)
    4. 4th Annual Report, 1 October 1991–30 September 1992 (93-2)
    5. 5th Annual Report, 1 October 1992–30 September 1993 (93-5)
    6. 6th Annual Report, 1 October 1993–30 September 1994 (95-2)
    7. 7th Annual Report, 1 October 1994–30 September 1995 (95-3)

*Numbers given in this style refer to items in the Chronological Bibliography given at the end of this report, e.g., 85-8 means the fifth entry in the list for 1985.

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2. STUDENTS AND OTHER PERSONNEL

A. Graduate Students

1. Michael R. Bailey
   (a) Academic department: Mechanical Engineering
   (b) Student period: September 1991–present
   (c) ONR support: September 1991–April 1993, September 1994–December 1995
   (d) Other support: Applied Research Laboratories IR&D Program, May 1994–August 1994
   (e) Degrees: M.S., May 1994; Ph.D., expected May 1997
2. Charles E. Bradley
   (a) Academic department: Mechanical Engineering
   (b) Student period: September 1987–May 1993
   (c) ONR support: July 1987–June 1993
   (d) Other support: UT Scholarship, September 1991–May 1992
   (e) Degrees: M.S., December 1990; Ph.D., May 1993
3. Samuel C. Clark
   (a) Academic department: Mechanical Engineering
   (b) Student period: September 1993–May 1994
   (c) ONR support: September 1993–January 1994
   (d) Other support: College of Engineering Fellowship
   (e) Degree: none
4. Frederick D. Cotaras
   (a) Academic department: Electrical and Computer Engineering
   (b) Student period: September 1983–December 1988
   (c) ONR support: September 1983–December 1988 (no salary support)
   (d) Other support: Canadian government (salary support)
   (e) Degrees: M.S., August 1985; Ph.D., May 1989

5. Lawrence J. Gelin
   (a) Academic department: Mechanical Engineering
   (b) Student period: September 1993–May 1995
   (c) ONR support: September 1993–May 1995
   (d) Other support: none
   (e) Degree: M.S., May 1995
6. Andrew J. Kimbrough
   (a) Academic department: Mechanical Engineering
   (b) Student period: September 1986–May 1987
   (c) ONR support: June 1986–May 1987
   (d) Other support: NASA
   (e) Degree: none
7. Ping-Wah Li
   (a) Academic department: Physics
   (b) Student period: September 1988–August 1993
   (c) ONR support: September 1991–May 1993
   (d) Other support: NIH, September 1989–August 1991; Applied Research Laboratories IR&D Program, June–September 1993
   (e) Degree: Ph.D., August 1993
8. David A. Nelson
   (a) Academic department: Mechanical Engineering
   (b) Student period: September 1981–December 1984
   (c) ONR support: September 1981–June 1985
   (d) Other support: NASA
   (e) Degree: M.S., December 1984
9. James A. Ten Cate
   (a) Academic department: Mechanical Engineering
   (b) Student period: September 1985–May 1992
   (c) ONR support: June 1985–May 1992
   (d) Other support: ONR Grant N00014-89-J-1103, Applied Research Laboratories IR&D Program, Packard Foundation, Texas Advanced Research Program, NSF, Newport Research Corp., UT Austin Univ. Res. Inst.
   (e) Degree: Ph.D., May 1992

10. Youseph Yazdi
    (a) Academic department: Electrical and Computer Engineering
    (b) Student period: September 1990–present
    (c) ONR support: September 1990–August 1992
    (d) Other support: David and Lucille Packard Foundation
    (e) Degree: none attributable to ONR support

B. Senior Personnel

1. David T. Blackstock — principal investigator

2. Frederick D. Cotaras — After completing all requirements for his doctorate in December 1988, Cotaras returned to his permanent post at Defence Research Establishment Atlantic, Dartmouth, NS, Canada. He returned to ARL:UT for a brief period in 1991 as a consultant.

3. Mark F. Hamilton — After a year at the University of Bergen as the Acoustical Society's F. V. Hunt Postdoctoral Fellow, Hamilton rejoined Nonlinear Acoustics Division (NAD) ARL:UT in 1984 as a postdoctoral fellow. In September 1985 he was appointed Assistant Professor in the Mechanical Engineering Department, The University of Texas at Austin, where he developed his own ONR supported program of research in nonlinear acoustics. However, he continued to collaborate with personnel in NAD on several of its ONR supported projects.

4. Christopher L. Morfey — Morfey (Institute of Sound and Vibration Research, University of Southampton, UK) was an annual consultant during the period 1984–89 and a Visiting Research Fellow for six months during 1991.

5. Jacqueline Naze Tjøtta — On leave from the Mathematics Institute, University of Bergen, Bergen, Norway, Naze Tjøtta was a Visiting Research Fellow at ARL:UT during the period 1987–90. Although only partly supported by ONR funds, she contributed significantly to the projects of Cotaras and Ten Cate.

6. Sigve Tjøtta — On leave from the Mathematics Institute, University of Bergen, Bergen, Norway, Tjøtta was a Visiting Research Fellow at ARL:UT during the period 1987–89. Although only partly supported by ONR funds, he contributed significantly to the projects of Cotaras and Ten Cate.

7. Wayne M. Wright — Wright (Physics Department, Kalamazoo College, Kalamazoo, Michigan) consulted annually for NAD/ARL:UT during 1984–94. He also spent his 1989–90 sabbatical leave (9 months) at NAD/ARL:UT as a Visiting Research Fellow. Although this appointment required no salary support from ONR funds, Wright contributed significantly to ONR supported projects during the period.

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3. PROJECTS

For purposes of this report, the broad headings below are used to classify the research that was done. The categories are not mutually exclusive, however, and the classification for some projects is arbitrary.

1. Nonlinear Ocean Acoustics
2. Propagation Problems
3. Reflection, Refraction, Interaction, and Scattering
4. Problems with Application to Medical Ultrasonics
5. Laboratory Equipment
6. Miscellaneous and General

3.1 Nonlinear Ocean Acoustics

For background see the final report for Contract N00014-75-C-0878 (86-1, pp. 42-44). Two projects begun during the earlier period were completed. First was a study of the effect of nonlinear propagation distortion on pulses that travel great distances in a stratified ocean (84-4, 85-2, 85-3, 85-7, 86-2, 86-3, 87-1). The work was carried out primarily by Cotaras, but Morfey (and to a minor extent R. Buckley) also contributed. The second project had to do with ocean properties important in nonlinear ocean acoustics, principally the coefficient of nonlinearity β. Empirical relations were developed that show the dependence of β and a related coefficient on pressure, temperature, and composition, for both fresh water and seawater (91-8, 93-4).

3.2 Propagation Problems

A wide variety of projects fall in this category. They are listed here roughly in chronological order.

a. Finite-amplitude propagation in bulk, air-filled porous material. For a summary of previous work on this project, see 86-1, pp. 44-47, and the journal article 87-3. The project was completed by Nelson early in the period covered by this report. Nelson's technical report (85-1) covers his master's thesis (84-8) but also contains a chapter of new material. See also 85-4 and 90-6.

b. Nonlinear propagation effects in a rectangular waveguide. The principals here were Ten Cate and Hamilton. The work was an outgrowth of Hamilton's Ph.D. research (84-5, 84-6) and Ten Cate's M.S. research (84-2). Collaboration between the two, begun in 1982–83 while both were graduate students, resumed when Hamilton rejoined NAD/ARL:UT as a postdoctoral fellow (1984–85) and Ten Cate returned in 1985 to begin his doctoral studies. The work was both theoretical and experimental. Two different problems were investigated:

   - Excitation of the waveguide in the 1,0 mode by a single-frequency source, which produces a family of harmonic distortion components (85-5, 86-4, 88-6).
   - Interaction of two noncollinear waves, one of low frequency in the 0,0 mode, the other of high frequency in the 1,0 mode (85-5, 85-9, 86-4, 87-2).

c. Intensity and absorption of finite-amplitude waves. This work by Blackstock was stimulated by the need to predict an effective measure of absorption for finite-amplitude ultrasound in tissue (88-3, 90-5).

d. Waves in a periodic medium. Bradley's pioneering work on this topic grew out of his desire to investigate the interaction of nonlinear propagation distortion with dispersion. However, the vehicle he chose for the study, propagation in a periodic waveguide, led him into a wide-ranging exploration of small-signal acoustical propagation in a periodic medium, including general aspects of phase and group velocity, as well as nonlinear propagation effects. The work was both theoretical and experimental. It resulted in several oral presentations (89-4, 90-3, 91-2, 93-8), a conference proceedings paper (90-7), Bradley's master's thesis (90-11, 91-4) and doctoral dissertation (93-1), and three journal articles (94-3, 94-4, 95-6). Largely because of the quality and success of his graduate work, Bradley was awarded the Acoustical Society's F. V. Hunt Postdoctoral Fellowship for 1993–94.

e. Momentum equation for plane progressive waves. This was a brief study carried out by Hamilton and Blackstock to publicize a little-known fact about nonlinear propagation distortion: for plane progressive waves nonlinear behavior is associated with nonlinear terms in the continuity equation and the equation of state; second-order terms disappear from the momentum equation (90-9).

f. Finite-amplitude radiation from a baffled piston. As part of his project on scattering of sound by sound (see Sec. 3.3.c below), Ten Cate made a very careful

and thorough study of the field of a single piston source driven hard at a single frequency (91-7, 93-6). Although good measurements of finite-amplitude radiation from a piston have been reported by previous investigators, Ten Cate's results are in a class by themselves. Dynamic range of his measurements frequently exceeds 100 dB, and comparison between measurement and theory (the "Bergen code"[1]) is shown in very fine detail.

g. Finite-amplitude waves in a medium having a distribution of relaxation processes. Li's project was motivated by concern about biomedical use of high-intensity ultrasound. (Despite the obvious connection with Sec. 3.4, the research is listed here because of its fundamental nature and also because of its possible application to other media, such as sediments.) The study was twofold. First, Li developed an equation to model finite-amplitude propagation in tissue. The absorption coefficient of tissue is known empirically to vary with (angular) frequency as ω^n, where n is generally in the range 1.0–1.2. Carstensen explained the peculiar frequency dependence by modeling tissue as a medium having a broad distribution of relaxation processes.[2] Using Carstensen's model, Li derived a nonlinear, integro-differential equation (a generalized Burgers equation) for propagation of finite-amplitude waves in a thermoviscous, multiply relaxing fluid. Some asymptotic solutions and some numerical solutions were found (92-4, 93-7, 93-9). In the second part of the study, Li applied his generalized Burgers equation to the problem of enhanced absorption, and concomitant temperature rise, in tissue exposed to intense ultrasound (93-7, 93-9, 94-1). He used the bioheat equation to calculate the increase in temperature.

h. Nonlinear distortion in propagation of aircraft noise. This was a project begun with ONR support but soon shifted to NASA support (95-2).

3.3 Reflection, Refraction, Interaction, and Scattering

a. Angular dependence of the coefficient of nonlinearity β. For ordinary propagation β depends only on the material property B/A of the fluid (the formula is $\beta = 1 + B/2A$). When two noncollinear wave fields interact, however, the nonlinear effect of one field on the other depends on the angle θ at which they intersect. Our work on this problem began under the previous contract, N00014-75-C-0867; see 84-2 and also 86-1, pp. 24-29. The topic is also closely related to the waveguide work described in Sec. 3.2.b above; see in particular 85-9. Hamilton and Blackstock wrote a journal article (88-1) to discuss the theoretical basis and validity of the expression $\beta = \cos\theta + B/2A$, which often appears in the literature.

b. Reflection and refraction at a plane interface between two fluids. This topic was Cotaras's doctoral project. In the beginning the goal was (1) to rederive

Snell's law and the law of specular reflection for plane finite-amplitude waves that are obliquely incident on a plane interface between two fluids, and (2) to test the resulting predictions by experiment. Initially an apparently successful derivation of a new form of Snell's law was obtained by physical arguments and various approximations, and a test experiment was planned (see 87-4, pp. 3-7, and also 87-7). However, the derivation was found to be too simple (and the approximations questionable), and very substantial difficulties were encountered in the experiment (88-5, pp. 2-4). The task was therefore changed to a theoretical investigation of oblique-angle refraction/reflection for weakly nonlinear waves, but with all sources of nonlinear effects taken into account, including motion of the interface, exact source conditions, and nonlinear relations among various field variables. The results are exceedingly complicated. However, it appears that Snell's law and specular reflection continue to hold, at least to second order, for finite-amplitude waves (89-1, 89-7). The Tjøttas were very helpful to Cotaras on theoretical aspects of this project.

c. Scattering of sound by sound. Ten Cate's doctoral research was intended to test new predictions by the Tjøttas[3] and Hamilton and Darvennes[4] on scattering of sound produced when two noncollinear beams of different frequency interact. In 1956 Ingard and Pridmore-Brown claimed[5] to have observed scattered sound outside the region where the two beams interact. The following year, and many times since, Westervelt,[6] on the basis of theoretical considerations, categorically denied the existence of scattered sound outside the interaction region. Ever since, the question has been highly controversial. Ten Cate performed new experiments, which were preceded and complemented by new theoretical work with the Tjøttas (89-8, 89-9, 91-1). Two sets of experiments were done. The first was on "self-scattering" of sound by sound, which occurs when only one source, driven at a single frequency, is used. The self-scattering manifests itself as extra sidelobes, called fingers, in the beam patterns of the second-harmonic and higher distortion components. Since the fingers exist outside the interaction region (in this case the beam pattern of the fundamental defines the interaction region), they qualify as scattered sound. Ten Cate's measurements (Sec. 3.2.f above) were outstandingly successful (91-7, 92-1, 93-6). No one before had so carefully measured the beam patterns and compared them with theory, particularly beyond the second harmonic. Moreover, he was the first to measure propagation curves, both for fingers and the product pattern lobes, and to quantify their different diminutions with distance. The second set of measurements was on crossed-beam scattering of sound by sound. Unfortunately, they were not so successful. Ideally, to avoid the presence of primary beam sidelobes, which interfere with observation of scattered sound, the experiment should be done with two Gaussian sources. Only one approximately Gaussian source was available, and it did not work well. The final results were inconclusive (92-1, 94-9). Any future attempt to observe crossed-beam scattering should be done with two true Gaussian sources.

d. Finite-amplitude waves in a three-layer complex. Yazdi, who was interested in biomedical ultrasonics, was given this project because of its potential application to tissue. The project was designed to use finite-amplitude sound in another traditional problem drawn from classical linear acoustics: transmission of sound from medium 1 into medium 2 and thence into medium 3. Frequently media 1 and 3 are the same, for example, when the application is to transmission loss through a panel or wall. Although several aspects of this problem could be explored, the one selected for Yazdi was a proposal (and theoretical prediction) by Nazarov[7] for measuring the coefficient of nonlinearity β. In this arrangement a layer of material (medium 2) in a water bath (media 1 and 3) is exposed to normally incident plane waves of finite amplitude. The source frequency is chosen so that the layer of material is transparent to the incident sound, which is composed of the fundamental and also the second-harmonic distortion generated in the water. In this case the only second-harmonic signal reradiated back to the source, which also serves as a receiver, is that from the standing wave second-harmonic field generated in the layer of material. Measurement of the reradiated signal allows β for the material to be determined (93-2, pp. 16-19). For initial simplicity a steel plate was used for the layer of material. Unfortunately before many measurements could be taken, the experiment was stopped because Yazdi transferred to a more traditional biomedical engineering program within the University. He had, however, made a very valuable contribution by designing and building a water tank and computer controlled positioning apparatus (see Sec. 3.5.b below). Although intended for Yazdi's experiment, the facility has proved extremely useful for several other NAD/ARL:UT projects.

e. Self-refraction in the field of a paraboloidal reflector. This was Gelin's project. Self-refraction is bending of rays due solely to finite-amplitude effects, as opposed to ordinary refraction, which is caused by sound speed variation in an inhomogeneous fluid. The propagation speed of any point on a finite-amplitude wave is $\frac{dx}{dt} = c_0 + \beta u$, where c_0 is the small-signal sound speed and u is the particle velocity at the point. Because of the dependence of $\frac{dx}{dt}$ on u, any variation of the particle velocity along a wavefront causes a change in direction of the wavefront, i.e., refraction. Self-refraction, first proposed by Whitham for shock waves,[8,9] is difficult to isolate in acoustical experiments because it is often mixed in with other effects, for example diffraction in the radiation field of a piston. However, the paraboloidal reflector, with a spark source at the focus, offers an ideal means for observing self-refraction: the (linear theory) plane wave reflected field is inhomogeneous, that is, the amplitude varies along the wavefronts. As a result, the wavefronts are predicted to become curved, concave for negative parts of the waveform, convex for positive parts. Gelin carried out the experiment in air. He made a large number of microphone measurements over the entire reflected field. Some peculiar effects were observed near the axis, probably due to the effect of the spark source (either local heating of the air or diffraction by the electrodes), which affected the paraxial reflected rays. Despite

these difficulties, self-refraction was very clearly observed (94-6, 94-7, 95-1).

3.4 Problems with Application to Medical Ultrasonics

a. Lithotripsy. Lithotripsy is the use of focused shock waves to break up kidney stones.[10] In the most common lithotripter, the Dornier machine, the shock wave source is an ellipsoidal reflector with an electric spark at its near focus. Both source and patient are in a water bath. The patient is positioned so that the kidney stone is located at the far focus of the ellipsoid. The pressure waveform at the far focus is a very short positive spike, of amplitude as high as 100 MPa and duration about 1 μs, followed by a negative tail of much longer duration and magnitude of order 10 MPa. Several elements – very high amplitude, focusing, diffraction, and cavitation – make lithotripsy a fascinating problem in nonlinear acoustics. The physics of lithotripsy prompted our general interest, beginning in 1987 (87-6, 88-2, 88-4). Work on specific topics followed; see Secs. 3.4.b and 3.4.d below.

b. Ellipsoidal focusing in air. This task was set up to study the interaction of finite-amplitude propagation, focusing, and diffraction in the field of an ellipsoidal reflector. Although lithotripsy was the intended application, the measurements were made in air because of our previous experience with airborne pulses generated by sparks (86-1, pp. 29-39). S. T. W. Cheng (M.E. undergraduate), Wright, and Blackstock carried out the study. Four different ellipsoidal reflectors were machined. Just as in lithotripsy, a spark located at the near focus generated the shock pulse. Although the waveform in air, an N wave, is different from that in water (a sharp positive peak followed by a long shallow negative tail), the physics of the reflection, focusing, and diffraction processes is the same. Pressure signatures of the reflected wave were measured at a sequence of points along the axis: (1) in the prefocus region, where the waveform observed was still an N, (2) in the focal region, where the waveform was U-shaped, and (3) in the postfocus region, where the waveform was a "sagging N" (89-6, pp. 9-11). In linear theory, passage through a three-dimensional focus is accompanied by waveform inversion, that is, a 180° phase shift. It is clear, therefore, that strong nonlinear distortion in the focal region and beyond greatly modified the phase change usually associated with focusing. Other measurements and observations were made (89-2, 89-3, 91-6).

c. Negative pulse generation by diffraction and other means. This was Bailey's M.S. research project. An isolated negative pressure pulse in water was needed for a medical ultrasonics experiment. Bailey began with an electric spark, which produces an almost pure positive pulse (the long negative tail that follows is frequently so weak as to be lost in the noise). Next he inverted the positive pulse by one of two methods: (1) reflection from the water surface, or (2) diffraction

from a circular aperture (the edge wave on axis behind the aperture is an inverted replica of the incident wave). Without further steps, the biomedical target would then have been exposed to the positive direct pulse as well as the desired negative pulse. To block out the direct pulse, Bailey made use of the fact that scattering from an object having a ragged edge produces an incoherent, very weak diffracted signal. For method (1), reflection from the water surface, he interposed a ragged-edge corprene barrier (either a plate or a disk) between the spark source and the target. For method (2), the aperture, he placed a small ragged-edge corprene disk in the aperture. In both cases the blocking object got rid of the direct wave and yet, because of the ragged edge, introduced no new coherent edge wave. The work was described in three oral reports (92-3, 94-5, 95-7), one conference proceedings (93-3), and Bailey's thesis (94-2). Method (1), with a plate used to block out the direct wave, was used in a biomedical experiment conducted at the University of Rochester. Mouse lungs and fruitfly larvae were exposed to isolated positive pulses and to isolated negative pulses (94-8, 96-1). The positive pulses were found to be at least as damaging as the negative pulses. This is an important finding. Heretofore investigators had assumed that tissue damage is due primarily to negative pressure.

d. Intensified cavitation produced by a duo ellipsoidal reflector system. Bailey's doctoral research project (at this writing about half finished) is built around a two-ellipsoid system that is designed to enhance the violence of cavitation collapse. The work is most concisely described by the following abstract of a paper to be presented at an upcoming meeting (96-2):

   "An underwater bubble is well known to grow in response to a strong negative acoustic pulse and then collapse because of inertial forces. Here we show that adding an auxiliary positive pulse, after collapse begins, intensifies the collapse. The negative-then-positive pulse sequence is produced by two ellipsoidal reflectors, each with an electrical spark at its near focus f_1 and beamed so that they share a common second focus f_2. The negative pulse is produced by a polyurethane (pressure release) ellipsoid, the positive by a brass (rigid) ellipsoid. A timing circuit controls the delay between the pulses. Cavitation is recorded by pitting (caused by bubble collapse) of an aluminum foil membrane, which is centered at f_2 and lies coplanar with the two crossed beams. When the brass reflector is fired alone, a narrow path of ~1-mm diameter pits appears. Firing the polyurethane reflector alone yields more widespread, ~0.1-mm diameter pits. When both are fired, a pitted X pattern shows the position of the two beams. If the delay between the two firings is 2–6 μs, the intersection of and the centerline between the paths erupts with deep pits. [Work supported by ONR.]"

3.5 Laboratory Equipment

a. Nonlinear acoustics laboratory upgrade. A substantial upgrade of the facilities for nonlinear acoustics experiments took place during the two-year period 1988-90. Support for the project came jointly from ONR and ARL:UT IR&D. Cotaras and Bradley were largely responsible for the design, equipment acquisition, and integration of a new measurement system, which made possible a wide variety of computer controlled experiments. See 89-6 and 90-4 for a detailed description. The new system played an extremely important role in all subsequent experiments, e.g., those described in Secs. 3.2.d, 3.3.d, 3.3.e, 3.4.b, 3.4.c, and 3.4.d, and in sonic boom model experiments supported by NASA.[11]

b. Ultrasonics tank with computer controlled positioner. In 1990-91 Yazdi greatly expanded the capability of the measurement system described above by adding a water tank and precision positioning system, which he designed and built himself. NIH provided funds for the motor controller/driver and the motors, which were the most expensive components. The tank and positioner, or in some cases the positioner by itself, were heavily used in several subsequent projects, for example, those described in Secs. 3.3.d, 3.3.e, 3.4.c, and 3.4.d, and the sonic boom experiments.[11]

3.6 Miscellaneous and General

a. Subharmonic generation and chaos in an acoustical resonance tube. This started out as Ten Cate's doctoral project. The premise was that a closed end resonance tube driven in one of its higher plane wave modes would excite subharmonics (in the lower modes of the tube). If the tube were driven hard enough, chaos would result. After careful study, however, Ten Cate found that the resonance tube is not a good candidate for chaotic response. A major problem is that raising the drive amplitude rapidly increases the losses and thus lowers the Q of the system. Since the resonance response curve cannot bend over far enough to produce hysteresis, bifurcation cannot occur. Ten Cate wrote an excellent white paper on the subject; see 86-6, Appendix A.

b. Thermoacoustics. Wright's work on the acoustical response of a cylindrical cavity to a modulated heat source (a current carrying wire) was reported in a journal article (87-5).

c. Reflection and transmission of a spherical wave at a concentric spherical interface. Reflection and transmission of plane waves normally incident on a plane interface between two lossless fluids (impedance $Z_1 = \rho_1 c_1$ on the incident wave side, $Z_2 = \rho_2 c_2$ on the transmitted wave side) is a classical subject. Blackstock and Morfey investigated the analogous problem for spherical waves

(91-3). Among the results: (1) The reflection and transmission coefficients R and T are complex and frequency dependent; the coefficients for a convex interface are the complex conjugates of those for a concave interface. (2) At high frequency R and T approach their plane wave values; at very low frequency $R \to -1$ (unless $\rho_1 = \rho_2$). (3) Perfect transmission requires both $\rho_1 = \rho_2$ and $c_1 = c_2$, not just $Z_1 = Z_2$.

d. Acoustitron. The acoustitron is a toroidal (doughnut shaped) waveguide driven from two or more (side-mounted) sources that are phased to assure unidirectional propagation around the waveguide. When the frequency is such that the (axial) circumference of the toroid is an integral number of wavelengths, resonance occurs. Resonance in a progressive wave field is very unusual and is what makes the acoustitron interesting. The high amplitude that may be obtained also makes it an attractive candidate for nonlinear acoustics. Bailey briefly investigated the acoustitron as a possible doctoral project. Two theoretical results were obtained: (1) an expression for the gain that can be achieved from the progressive wave resonance, (2) a calculation of the distorted waveform that develops because of nonlinear propagation effects. Some preliminary experiments were also done. See 95-2, pp. 8-11, for details. In the end Bailey preferred the duo ellipsoid project (Sec. 3.4.d above) for his doctoral work, and the acoustitron project was set aside for a future student.

e. General. Other work associated in some way with Grant N00014-89-J-1109, Contract N00014-84-K-0574, or one of its predecessors is as follows: several reviews of nonlinear acoustics (86-5, 89-5, 90-2, 90-10, 95-4, 95-5), journal articles on earlier work, either appearing for the first time or reprinted in books (84-9, 84-10, 85-6), historical sketches (84-7, 92-2), a paper on acoustics education (88-7), and a book (90-8).

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4. SUMMARY

Research on nonlinear acoustics was performed during the period 1984–95. The major areas included in the report are as follows: nonlinear ocean acoustics; propagation problems; reflection, refraction, interaction, and scattering; problems associated with medical ultrasonics; and miscellaneous topics. The research led to five master's degrees and four doctorates among seven students. One other doctorate was in progress at the time the grant ended. Also participating in the research were one postdoctoral fellow, four visiting faculty members from other universities, and a visitor from a Canadian naval laboratory. Among the public disclosures of the research were 15 journal articles (and two more submitted but not yet published), 10 papers in conference proceedings, 6 book chapters, 39 papers presented orally at national and international meetings, 9 theses and dissertations, and 18 technical reports.

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1984–1996
Grant N00014-89-J-1109 (10/1/88 – 12/31/95)
and
Contract N00014-84-K-0574 (8/1/84 – 12/31/88)

Code			ONR Grant/Contract		
B	=	chapter in a book	1109	=	N00014-89-J-1109, ended 12/31/95
J	=	journal publication			
Js	=	submitted for journal publication	0574	=	N00014-84-K-0574, ended 12/31/88
O	=	oral presentation	0867	=	N00014-75-C-0867 ended 8/31/84
P	=	paper in a proceedings			
T	=	thesis or dissertation	0805	=	N00014-82-K-0805 ended 11/30/84
TR	=	technical report			

1984[1]

ONR Contract	Code		
0867	O,P	1.	S. Saito and T. G. Muir, "Simple model for analyzing a parametric focusing source," Meeting of the Acoustical Society of Japan, 29-31 March 1984, Tokyo, Japan. PAPER: Proceedings, pp. 33-40 (In Japanese).
0867	TR	2.	J. A. Ten Cate, "Nonlinear Interaction of Two Noncollinear Sound Waves in a Rectangular Waveguide," Technical Report ARL-TR-84-16, Applied Research Laboratories, The University of Texas at Austin, June 1984. (AD A144440)
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0805 0574	O	4.	F. D. Cotaras, C. L. Morfey, and D. T. Blackstock, "Nonlinear effects in long range underwater propagation," Paper Q6, 108th Meeting, Acoustical Society of America, Minneapolis, 8-12 October 1984. ABSTRACT: *J. Acoust. Soc. Am.* **76**, S39 (1984).

[1]Items 84-1,2,3 pertain to work completed under the predecessor contract, N00014-75-C-0867. They are included here to maintain continuity of the numbering system used in the final report (86-1) for that contract.

ONR Contract	Code		
0867	J	[a]5.	M. F. Hamilton and F. H. Fenlon, "Parametric acoustic array formation in dispersive fluids," *J. Acoust. Soc. Am.* **76**, 1474-1492 (1984).
0867	J	[a]6.	M. F. Hamilton, "Effects of noncollinear interaction on the parametric acoustic array," *J. Acoust. Soc. Am.* **76**, 1493-1504 (1984).
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[a]Primary support for this work came from ONR Contract N00014-79-C-0624 with Pennsylvania State University.
[b]Primary support for this work came from NASA Grant NSG 3198.

1985

ONR Contract	Code		
0867 0574	TR	[b]1.	D. A. Nelson, "Interaction of Finite-Amplitude Sound with Air-Filled Porous Materials," Technical Report ARL-TR-85-15, Applied Research Laboratories, The University of Texas at Austin, March 1985. (AD A155986)
0805 0574	O	2.	C. L. Morfey and J. M. Estes, "Long-range nonlinear propagation of explosive waveforms in the ocean," Paper M10, 109th Meeting, Acoustical Society of America, Austin, 8-12 April 1985. ABSTRACT: *J. Acoust. Soc. Am.* **77**, S30 (1985).
0805 0574	O	3.	R. Buckley, "Time domain approach to the propagation of nonlinear acoustic pulses near caustics," Paper M12, 109th Meeting, Acoustical Society of America, Austin, 8-12 April 1985. ABSTRACT: *J. Acoust. Soc. Am.* **77**, S30-31 (1985).
0867 0574	O	[b]4.	D. A. Nelson and D. T. Blackstock, "Propagation and attenuation of intense tones in air-filled porous materials," Paper V7, 109th Meeting, Acoustical Society of America, Austin, 8-12 April 1985. ABSTRACT: *J. Acoust. Soc. Am.* **77**, S47 (1985).
0867 0574	O	5.	M. F. Hamilton and J. A. Ten Cate, "Higher-order finite amplitude modes in a rectangular waveguide," Paper V10, 109th Meeting, Acoustical Society of America, Austin, 8-12 April 1985. ABSTRACT: *J. Acoust. Soc. Am.* **77**, S47 (1985).
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0574	TR	8.	D. T. Blackstock, "Nonlinear Acoustics: Long Range Underwater Propagation, Air-Filled Porous Materials, and Noncollinear Interaction in a Waveguide," First Annual Summary Report under Contract N00014-84-K-0574, Technical Report ARL-TR-85-36, Applied Research Laboratories, The University of Texas at Austin, 28 October 1985. (AD A161037)
0574	O	[c]9.	M. F. Hamilton and J. A. Ten Cate, "A coefficient of nonlinearity for noncollinear plane-wave interaction," Paper S1, 110th Meeting, Acoustical Society of America, Nashville, 4-8 November 1985. ABSTRACT: *J. Acoust. Soc. Am.* **78**, S39 (1985).

[c]Hamilton's work supported in part by ONR Contract N00014-85-K-0708.

1986

ONR Contract	Code		
0867	TR	1.	D. T. Blackstock, "Research in Nonlinear Acoustics," Final Report under Contract N00014-75-C-0867, Technical Report ARL-TR-86-19, Applied Research Laboratories, The University of Texas at Austin, 2 July 1986. (AD A172634)
0805 0867 0574	O	2.	F. D. Cotaras, D. T. Blackstock, and C. L. Morfey, "Beyond what distance are finite-amplitude effects unimportant?" 12th International Congress on Acoustics, Associated Symposium on Underwater Acoustics, Halifax, Canada, 16-18 July 1986.
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0867 0574	O,P	5.	D. T. Blackstock, "Nonlinear behavior of sound waves," Plenary Paper 3, 12th International Congress on Acoustics, Toronto, Canada, 24-31 July 1986. SUMMARY (6 pages): Proceedings, Vol. III, Plenary 3 (1986).
0574	TR	6.	D. T. Blackstock, "Nonlinear Acoustics: Long Range Underwater Propagation, Noncollinear Interaction, Reflection and Refraction, and Subharmonic Generation," Second Annual Summary Report under Contract N00014-84-K-0574, Technical Report ARL-TR-86-36, Applied Research Laboratories, The University of Texas at Austin, 5 December 1986. (AD A175475)

1987

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0805 0867 0574	B	1.	F. D. Cotaras, D. T. Blackstock, and C. L. Morfey, "Beyond what distance are finite-amplitude effects unimportant?" in **Progress in Underwater Acoustics**, H. M. Merklinger, ed. (Plenum Press, New York, 1987), pp. 395–402.
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[d]Supported in part by an NIH grant with University of Rochester.

1988

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0574	J	[c]1.	M. F. Hamilton and D. T. Blackstock, "On the coefficient of nonlinearity β in nonlinear acoustics," *J. Acoust. Soc. Am.* **83**, 74–77 (1988).
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0574	TR	5.	D. T. Blackstock, "Nonlinear Acoustics: Reflection and Refraction, Scattering of Sound by Sound, and Periodic Media," Fourth Annual Summary Report under Contract N00014–84–K–0574, Technical Report ARL–TR–88–30, Applied Research Laboratories, The University of Texas at Austin, 30 June 1988. (AD A197614)
0867	J	6.	M. F. Hamilton and J. A. Ten Cate, "Finite amplitude sound near cutoff in higher order modes of a rectangular duct," *J. Acoust. Soc. Am.* **84**, 327–334 (1988).
Gen[§]	O	7.	D. T. Blackstock, I. J. Busch-Vishniac, M. F. Hamilton, and E. L. Hixson, "Graduate acoustics at The University of Texas at Austin," Paper ZZ9, 116th Meeting, Acoustical Society of America, Honolulu, 14-18 November 1988. ABSTRACT: *J. Acoust. Am.* **84**, S167 (1988).

[e]Supported in part by a grant from Bureau of Engineering Research, College of Engineering, The University of Texas at Austin.

[§]Supported in part by ONR, under several different grants and contracts, and by several other sponsors.

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1109 0574	T,TR	1.	F. D. Cotaras, "Reflection and Refraction of Finite Amplitude Acoustic Waves at a Fluid-Fluid Interface," Ph.D. dissertation, Electrical and Computer Engineering Department, The University of Texas at Austin, May 1989. ABSTRACT: *J. Acoust. Soc. Am.* **92**, S201 (1991). Also issued as Technical Report ARL-TR-89-1, Applied Research Laboratories, The University of Texas at Austin, 3 January 1989. (AD A209800)
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1109	O	[f,g]3.	S. T. W. Cheng, M. R. Jones, D. T. Blackstock, and W. M. Wright, "Focusing of an N wave by an ellipsoidal reflector: An experiment in air," Paper TT12, 117th Meeting, Acoustical Society of America, Syracuse, 22-26 May 1989. ABSTRACT: *J. Acoust. Soc. Am.* **85**, S113 (1989).
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[f]Supported in part by Applied Research Laboratories IR&D program.
[g]Supported in part by Texas Advanced Research Program.

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1109 0574	O,P	[f]7.	F. D. Cotaras, D. T. Blackstock, S. Tjøtta, and J. Naze Tjøtta, "An analysis of the reflection and refraction of finite-amplitude plane waves at a plane fluid-fluid interface," 13th International Congress on Acoustics, Belgrade, Yugoslavia, 24–31 August 1989. Proceedings, Vol. I, pp. 263–266 (1989).
1109 0574	O,P	[f]8.	J. Naze Tjøtta, J. A. Ten Cate, and S. Tjøtta, "Scattering of sound by sound: Effects of boundary conditions," 13th International Congress on Acoustics, Belgrade, Yugoslavia, 24–31 August 1989. Proceedings, Vol. I, pp. 287–290 (1989).
1109 0574	O	[f]9.	J. Naze Tjøtta, J. A. Ten Cate, and S. Tjøtta, "Effects of boundary conditions on the propagation and interaction of finite amplitude sound beams," Paper PP2, 118th Meeting, Acoustical Society of America, St. Louis, 27 November–1 December 1989. ABSTRACT: *J. Acoust. Soc. Am.* **86**, S106 (1989).

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1109 0574 0867	O	[h]2.	D. T. Blackstock and J. D. Maynard, "Demonstration of nonlinear acoustics phenomena," Paper L6, 119th Meeting, Acoustical Society of America, Pennsylvania State University, State College, Pennsylvania, 21-25 May 1990. ABSTRACT: *J. Acoust. Soc. Am.* **87**, S32 (1990).
1109	O	3.	C. E. Bradley, "Linear and nonlinear acoustic propagation in a periodic waveguide," Paper TT9, 119th Meeting, Acoustical Society of America, Pennsylvania State University, State College, Pennsylvania, 21-25 May 1990. ABSTRACT: *J. Acoust. Soc. Am.* **87**, S113 (1990).
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0574 0867	O,P	[b]6.	D. A. Nelson and D. T. Blackstock, "Harmonic generation, propagation and attenuation for finite-amplitude tones in an air-filled porous material," 12th International Symposium on Nonlinear Acoustics, Austin, 27-31 August 1990, **Frontiers of Nonlinear Acoustics – 12th ISNA**, M. F. Hamilton and D. T. Blackstock, eds. (Elsevier Applied Science, London, 1990), pp. 621–626.

[h]Maynard's support for this work came from an ONR contract with Pennsylvania State University.
[i]Supported in part by NIH Grant CA 49172.

ONR Grant	Code		
1109 0574	O,P	7.	C. E. Bradley, "Linear and nonlinear acoustic propagation in a periodic waveguide," 12th International Symposium on Nonlinear Acoustics, Austin, 27-31 August 1990, in **Frontiers of Nonlinear Acoustics – 12th ISNA**, M. F. Hamilton and D. T. Blackstock, eds. (Elsevier Applied Science, London, 1990), pp. 315–320.
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1109 0574	T	11.	C. E. Bradley, "Acoustic Bloch Wave Propagation in a Periodic Waveguide," M.S. thesis, Mechanical Engineering Department, The University of Texas at Austin, December 1990.

[j]Hamilton's support for this work came from ONR Grant N00014-89-J-1003.
[k]Supported in part by ONR Grant N00014-J-90-1373.

1991

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1109 0574	J	[f]1.	J. Naze Tjøtta, J. A. Ten Cate, and S. Tjøtta, "Effects of boundary conditions on the nonlinear interaction of sound beams," *J. Acoust. Soc. Am.* **89**, 1037–1049 (1991).
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1109	O	[l]3.	D. T. Blackstock and C. L. Morfey, "Reflection and transmission of spherical waves incident on a concentric spherical interface," Paper 7PA1, 121st Meeting, Acoustical Society of America, Baltimore, 29 April–3 May 1991. ABSTRACT: *J. Acoust. Soc. Am.* **89**, 1971 (1991).
1109 0574	TR	4.	C. E. Bradley, "Acoustic Bloch Wave Propagation in a Periodic Waveguide," Technical Report ARL-TR-91-19, Applied Research Laboratories, The University of Texas at Austin, 24 July 1991. (AD A244068)
1109	TR	5.	D. T. Blackstock, "Nonlinear Acoustics: Propagation in a Periodic Waveguide, Scattering of Sound by Sound, Propagation Through a Three-Layer Fluid, and Nonlinearity Parameters of Sea Water," Third Annual Summary Report under Grant N00014-89-J-1109, Technical Report ARL-TR-91-21, Applied Research Laboratories, The University of Texas at Austin, 19 August 1991. (AD A241294)
1109	O	[f,g]6.	W. M. Wright and D. T. Blackstock, "Experimental study of ellipsoidal focusing of spark-produced N waves in air," Paper 7PA6 (invited), 122nd Meeting, Acoustical Society of America, Houston, 4-8 November 1991. ABSTRACT: *J. Acoust. Soc. Am.* **90**, 2339(A) (1991).
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[l]Supported in part by NASA Grant NAG-1-1204 and University of Southampton.
[m]Also supported by ONR Grant N00014-89-J-1103, Applied Research Laboratories IR&D Program, David and Lucille Packard Foundation, Texas Advanced Research Program, NSF, Newport Research Corp., and UT University Research Institute.

1991 (continued)

ONR Grant	Code		
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1992

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1993

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